SCA Wettability Short Course

Advanced measurements of wettability: Pore Scale Imaging

Dr. Matthew Andrew
Oil and Gas Technologist
Carl Zeiss Microscopy GmbH

Outline

1 Introduction – Why look at the pore scale?

2 Measuring spatially resolved contact angles

3 One application in depth – a heterogeneous carbonate

4 New developments – towards automation

5 Applications – flow, real systems and curvature

6 Other technologies – cryo SEM

Who am I?

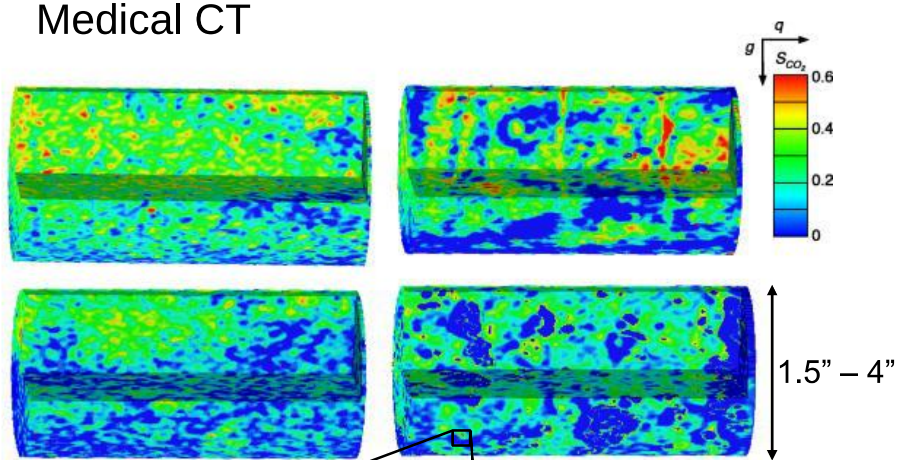
Undergraduate and Masters from Queens' College, Cambridge in Geological Sciences. PhD from Imperial College in Petroleum Engineering, where I developed the first reservoir condition in situ rig, integrated with the Versa XRM, allowing for pore-scale imaging of multiphase flow.

Now I direct O&G & Geoscience within Zeiss Microscopy

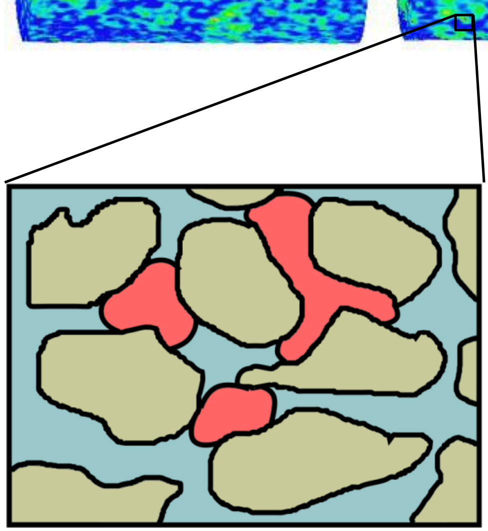
- Menke, Reynolds, Andrew et al., 2017. 4D multi-scale imaging of reactive flow in carbonates: Assessing the impact of heterogeneity on dissolution regimes using streamlines at multiple length scales. Chemical Geology (In Press)
- Andrew et al. 2018. The Usage of Modern Data Science in Segmentation and Classification: Machine Learning and Microscopy
- Andrew, M., Bijeljic, B. & Blunt, M.J., 2013. Pore-scale imaging of geological carbon dioxide storage under in situ conditions. Geophysical Research Letters, 40(15), pp.3915–3918.
- Andrew, M., Bijeljic, B. & Blunt, M.J., 2014. New frontiers in experimental geoscience : X-ray microcomputed tomography and fluid flow., Microscopy and Analysis (February), pp.4–7.
- Andrew, M., Bijeljic, B. & Blunt, M.J., 2014a. Pore-by-pore capillary pressure measurements using X-ray microtomography at reservoir conditions: Curvature, snap-off, and remobilization of residual CO2. Water Resources Research, 50, pp.8760–8774.
- Andrew, M., Bijeljic, B. & Blunt, M.J., 2014b. Pore-scale contact angle measurements at reservoir conditions using X-ray microtomography. Advances in Water Resources, 68, pp.24–31. Available at: http://dx.doi.org/10.1016/j.advwatres.2014.02.014.
- Andrew, M., Bijeljic, B. & Blunt, M.J., 2014c. Pore-scale imaging of trapped supercritical carbon dioxide in sandstones and carbonates. International Journal of Greenhouse Gas Control, 22, pp.1–14. Available at: http://dx.doi.org/10.1016/j.ijggc.2013.12.018.
- Andrew, M.G. et al., 2015. The Imaging of Dynamic Multiphase Fluid Flow Using Synchrotron-Based X-ray Microtomography at Reservoir Conditions. Transport in Porous Media, 110, pp.1–24.
- Menke, H.P. et al., 2015. Dynamic Three-Dimensional Pore-Scale Imaging of Reaction in a Carbonate at Reservoir Conditions. Environmental Science & Technology, p.150323102837000. Available at: http://pubs.acs.org/doi/abs/10.1021/es505789f.

Continuum vs. Pore Scale

Continuum Scale
Medical CT



Krevor *et al.* 2012

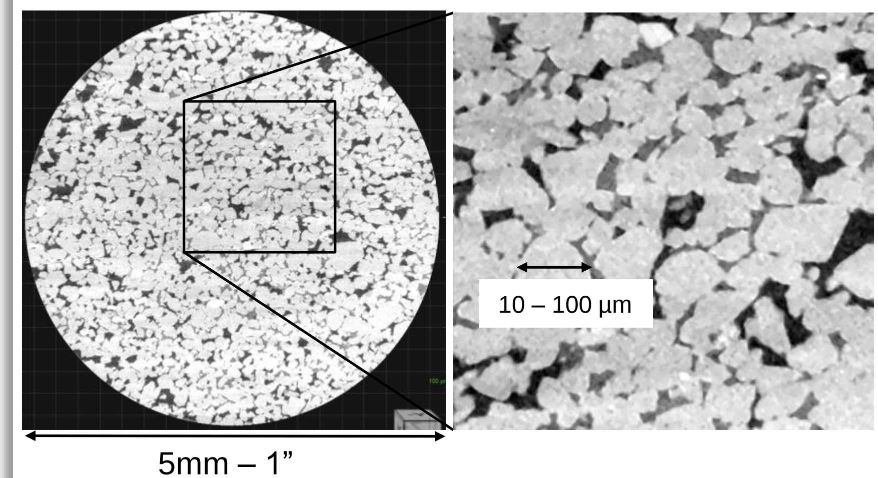


Voxel Size: 0.5mm

Each voxel consists of averaged property, giving a saturation distribution.

This saturation can then be averaged across the core, to form a relative permeability curve, or can be associated with core scale features affecting flow (e.g. sedimentary structures / bedding layers)

Pore Scale
XRM

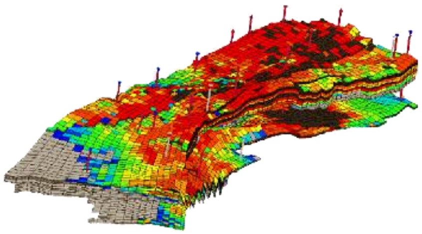


Voxel Size: <1µm

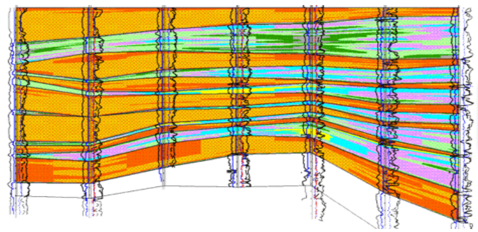
Each voxel uniquely describes a single phase (e.g. rock grain, oil or brine), giving truly pore-scale information.

This information can be used to examine connected vs. disconnected saturation, wettability changes, changes in saturation structure or a wide range of different phenomena fundamentally controlling macroscopic flow and transport phenomena.

Extensive Existing Paradigm for Dealing with Reservoir Scale Heterogeneity



Static reservoir geomodel

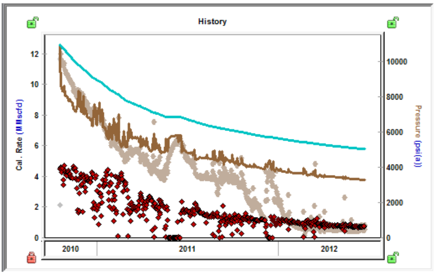


Wireline logging, lithological classification & core correlation

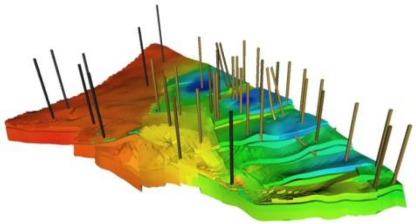
Core plug sampling

Bridge to the pore scale

History matching



Production prediction & management decisions



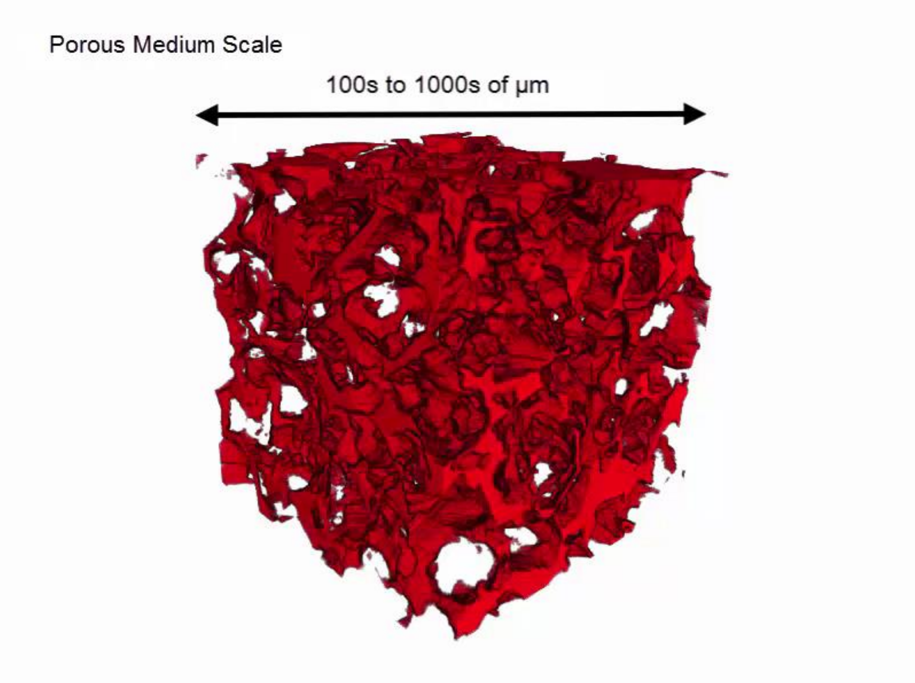
Population of dynamic reservoir model

Experimental measurement of petrophysical properties

Pore scale vs. grain scale: Fluid flow rooted at the pore scale

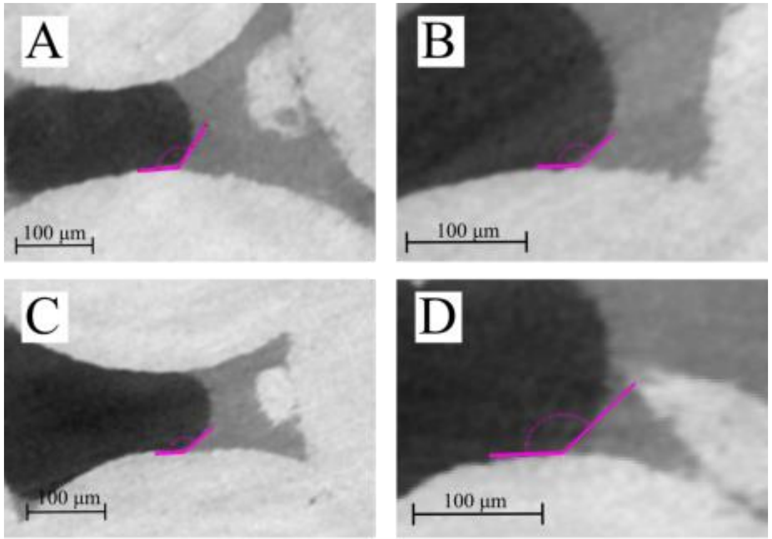
Flow fundamentally rooted at the scale of the pore throat

Single phase: Hagen–Poiseuille equation



$$q = \frac{r^2}{8\mu}\frac{dP}{dx}$$

Multi-phase: Governs pore snap-off & invasion capillary pressure

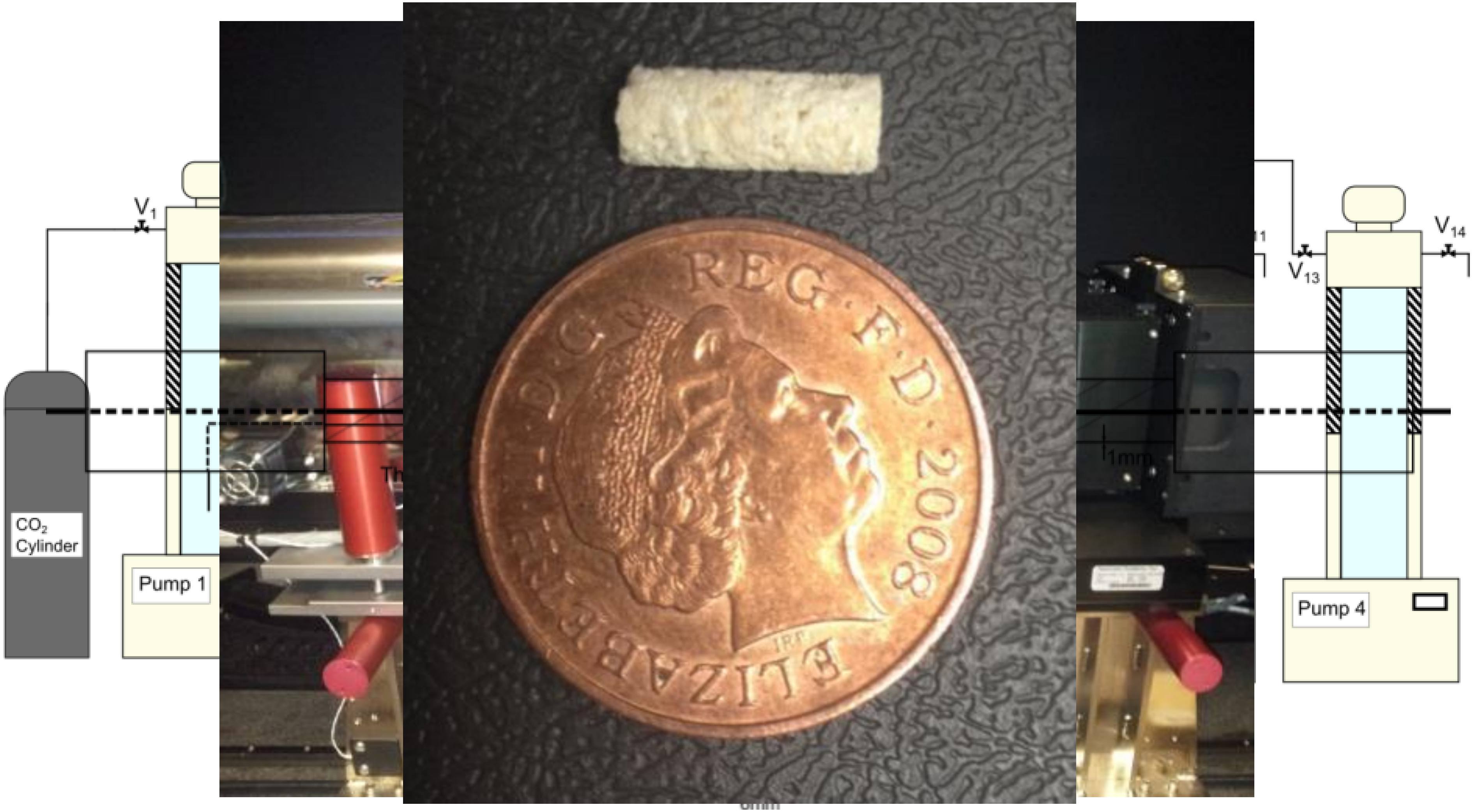


Threshold capillary pressures:

Drainage: $$P_{cow} = \frac{2\sigma_{ow}\cos\theta_{owr}}{r},$$

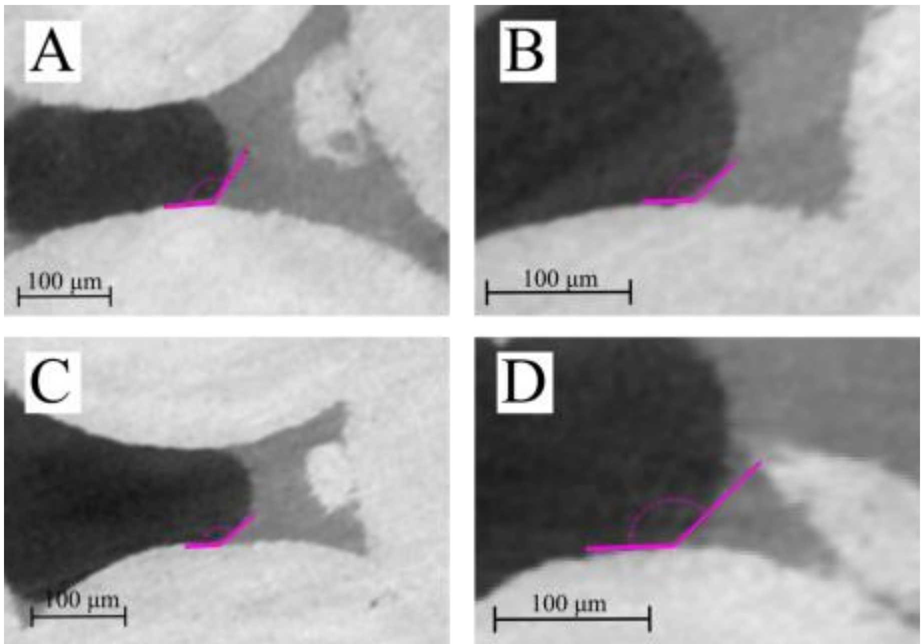
Imbibition: $$P_{c-so} = \frac{1}{r} \times \sigma \left(\cos\theta_a - \frac{2\sin\theta_a}{\cot\beta_1 + \cot\beta_2} \right)$$

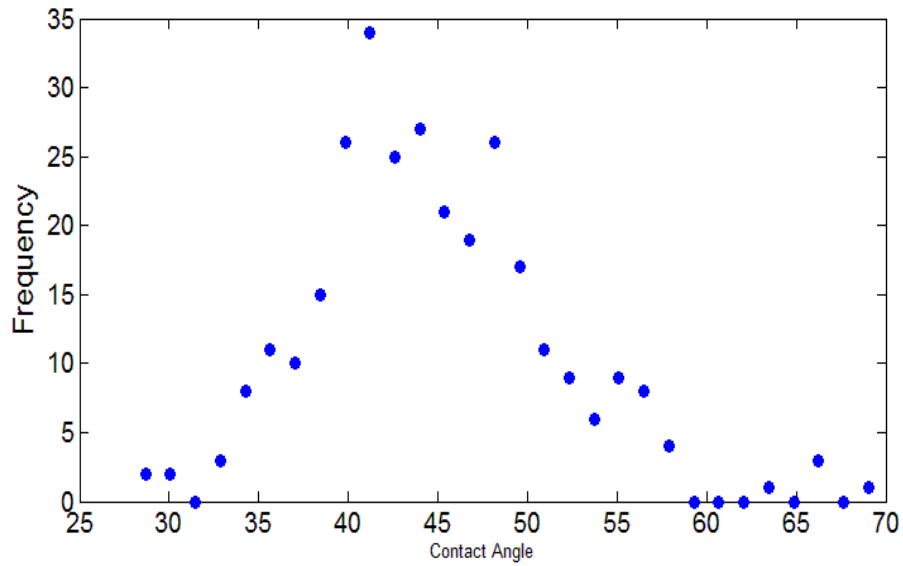
Experiments



Contact angle measurement

Measuring on real systems

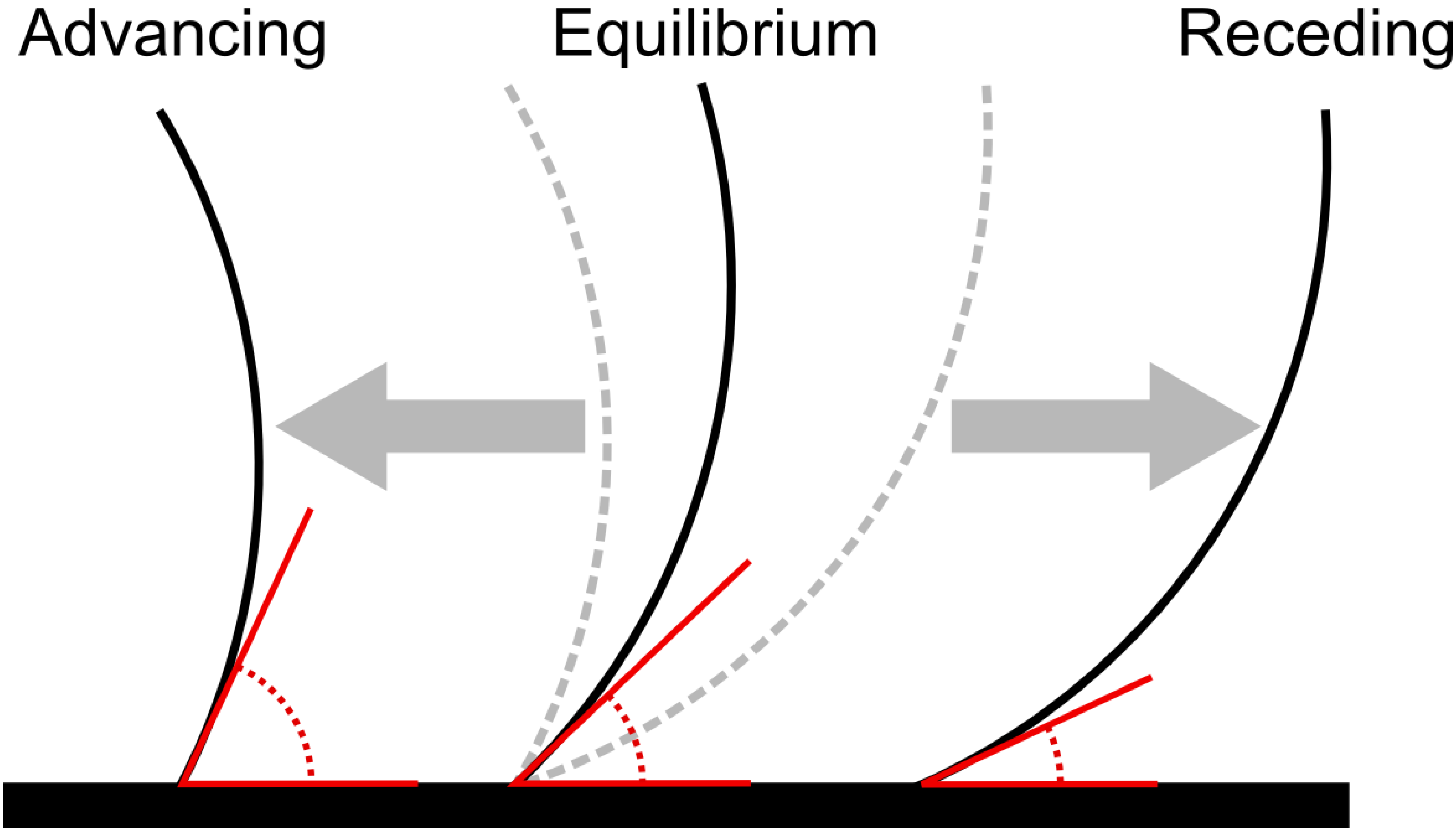




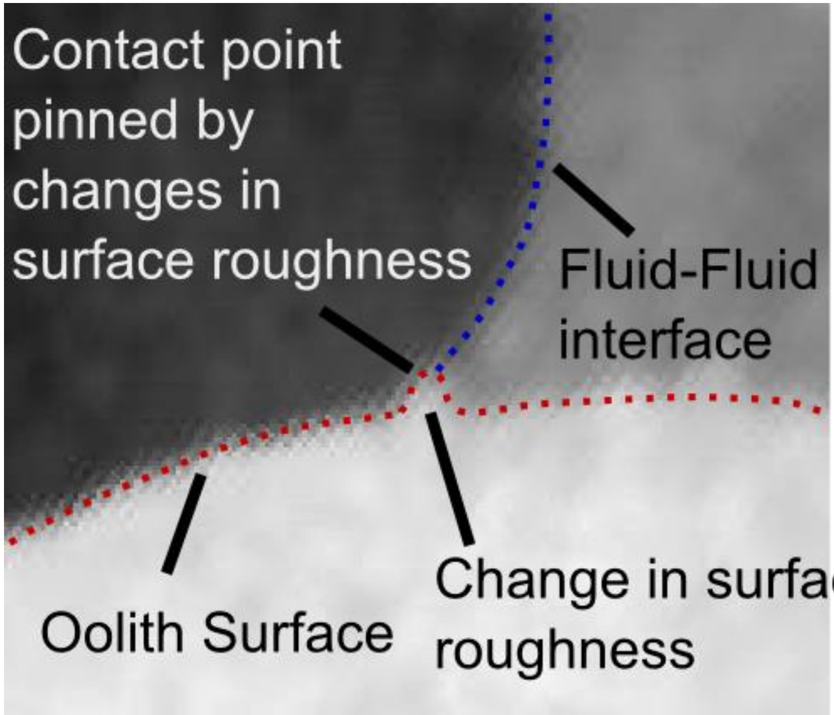
Contact angle measured directly on the resampled dataset.

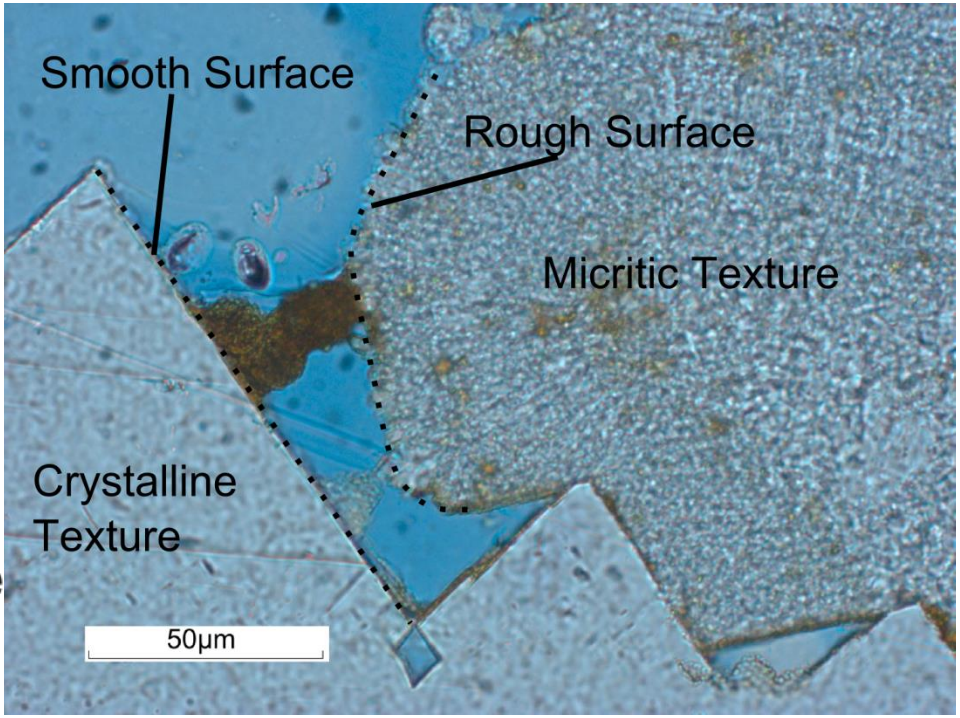
45±10º

Contact angle distribution – contributing factors

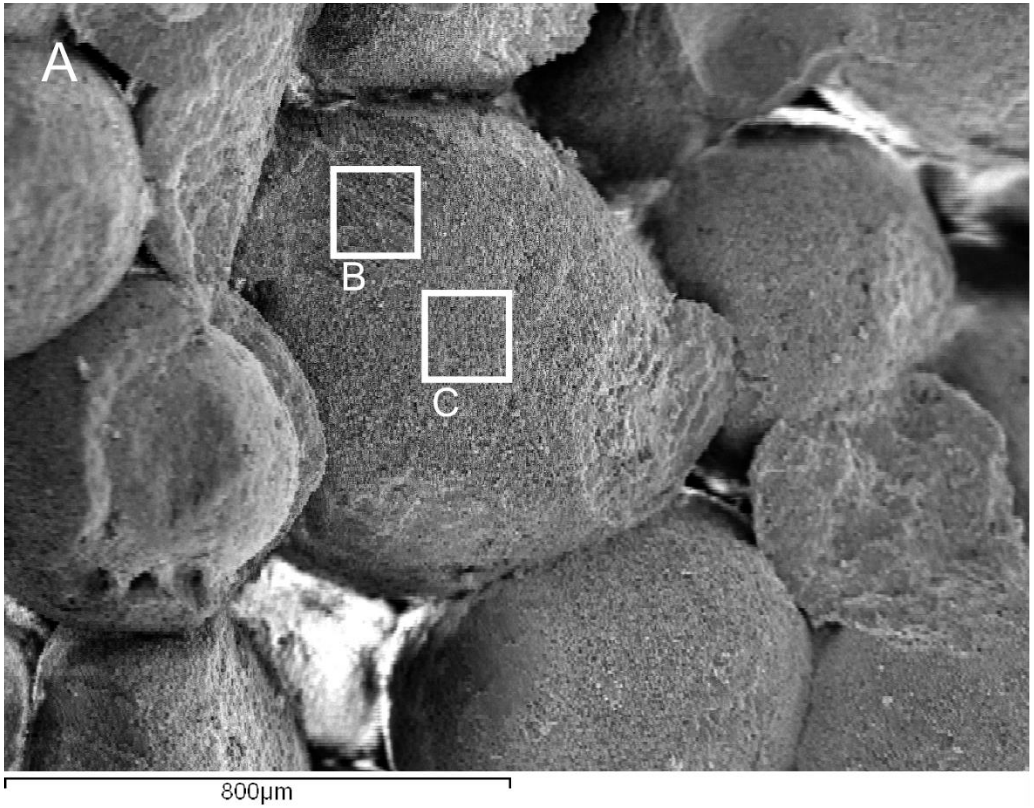


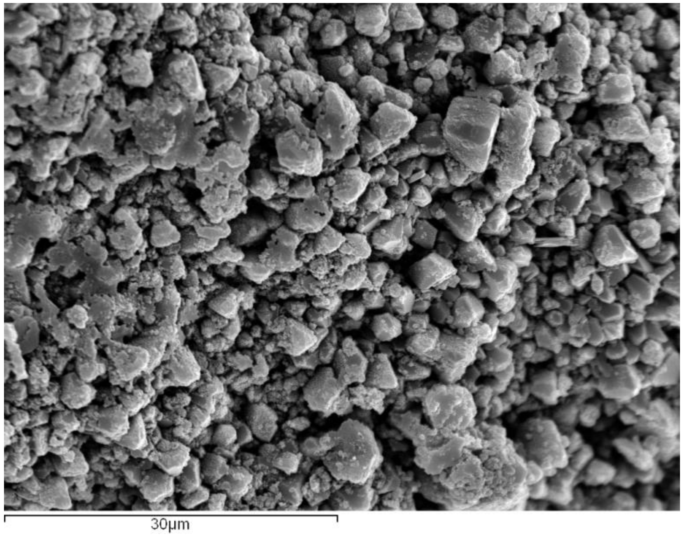
Contact angle distribution – contributing factors

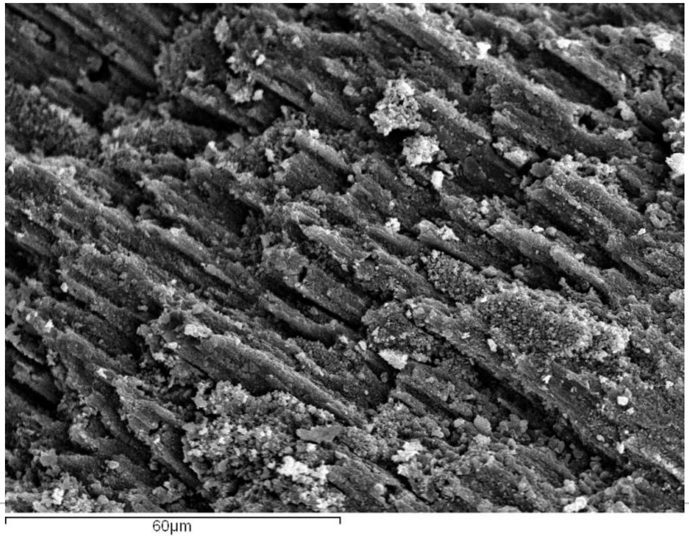




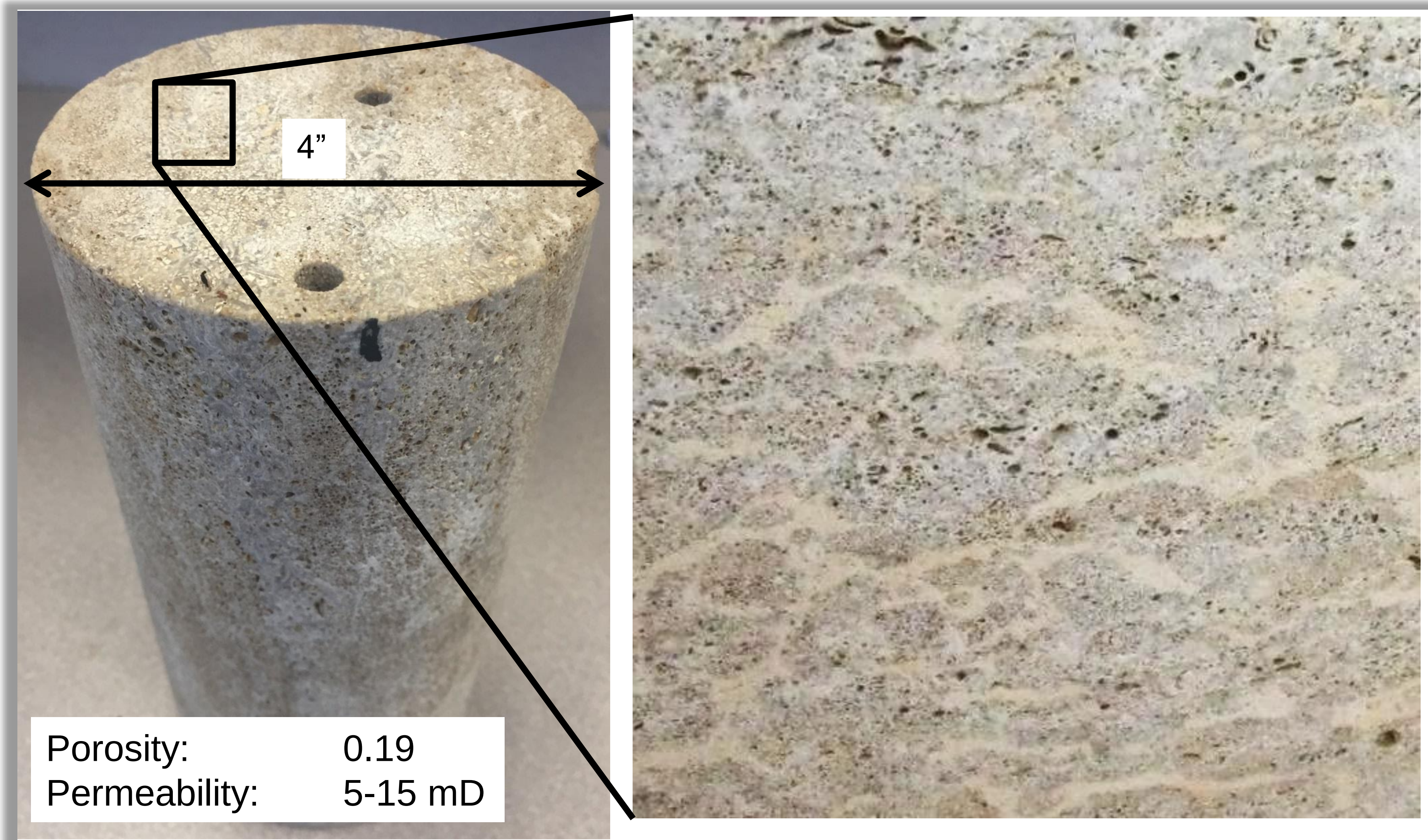
Contact angle distribution – contributing factors



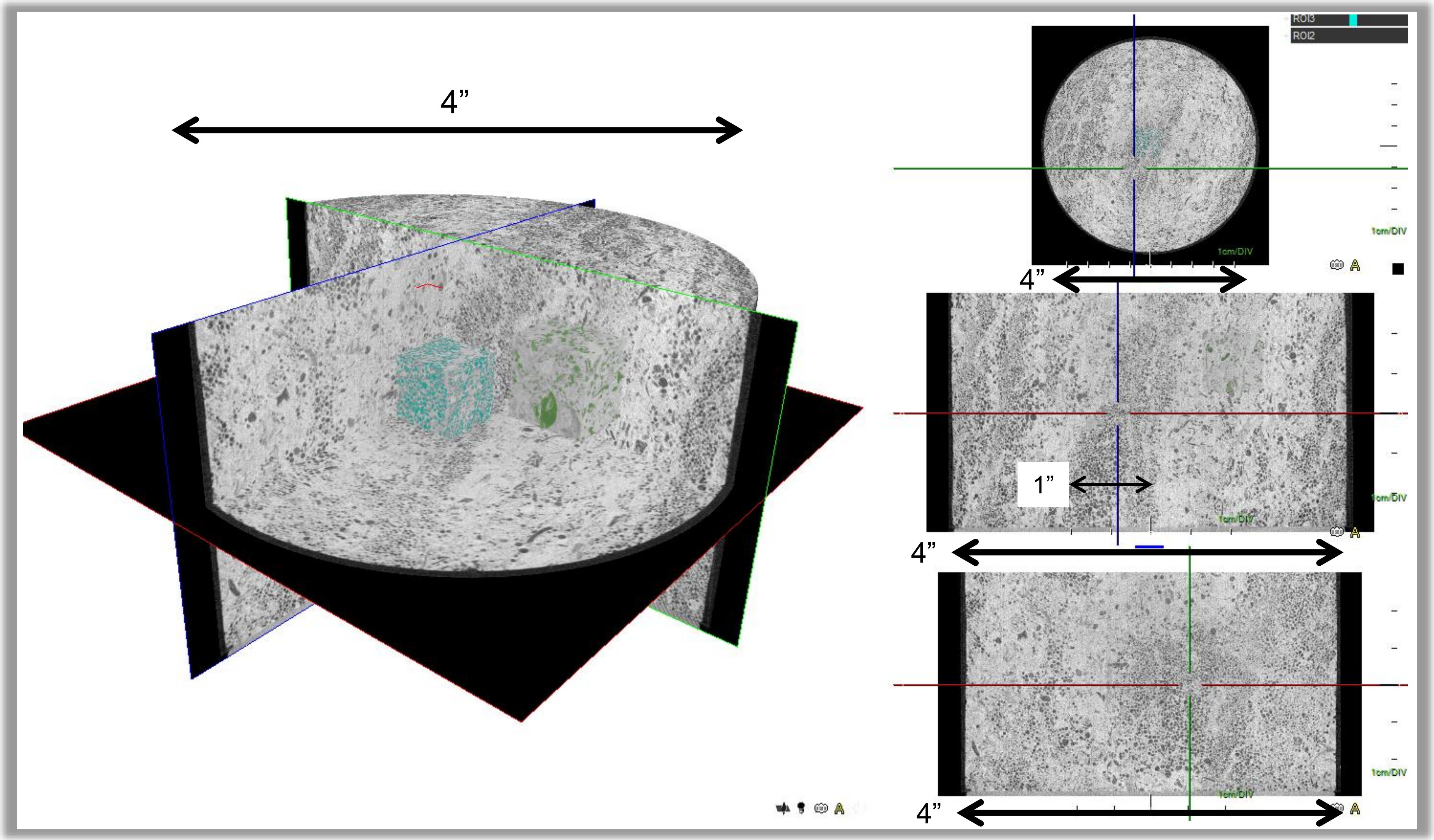




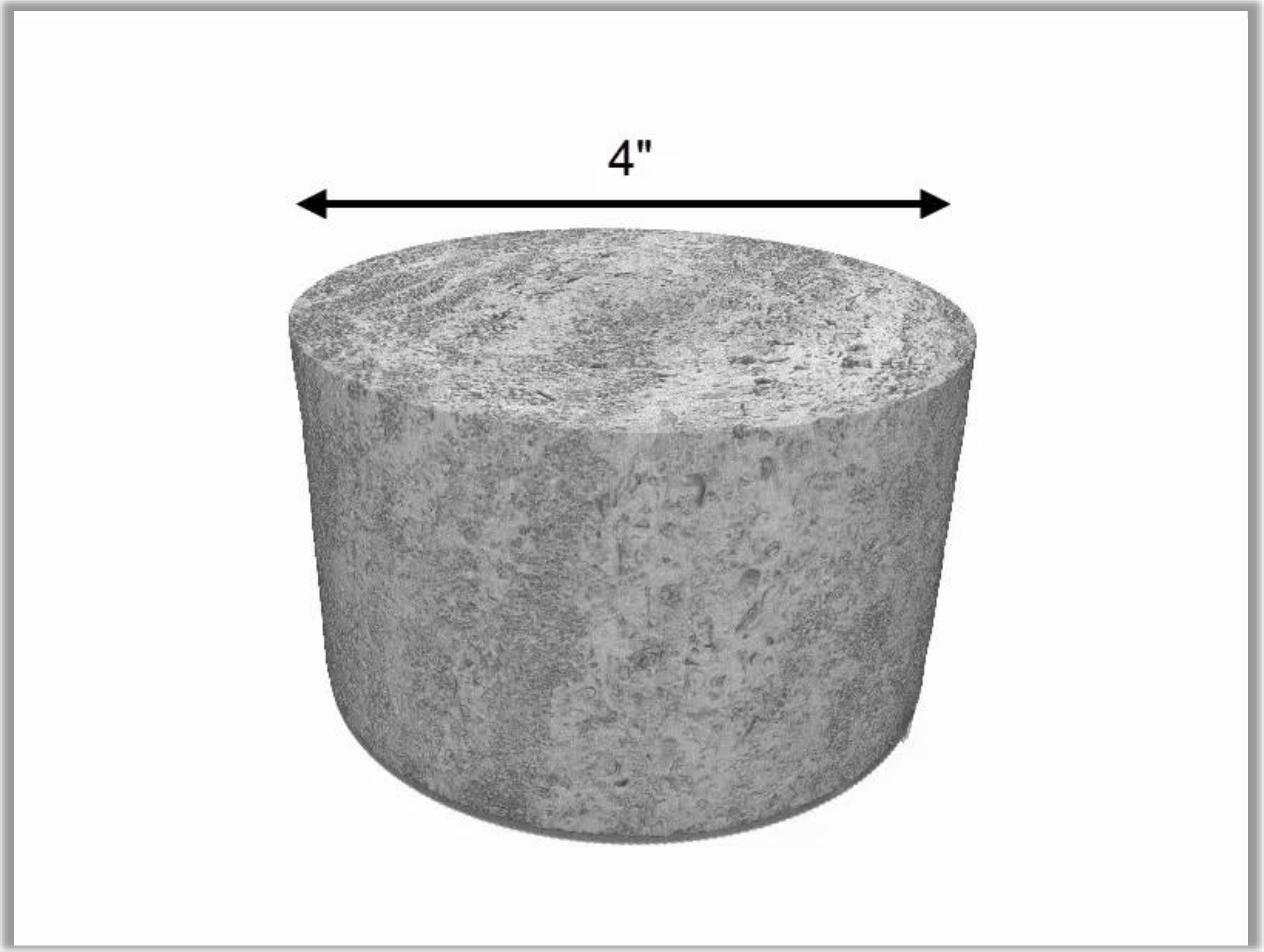
Heterogeneous Carbonate Sample



Results
Macroscopic Scanning



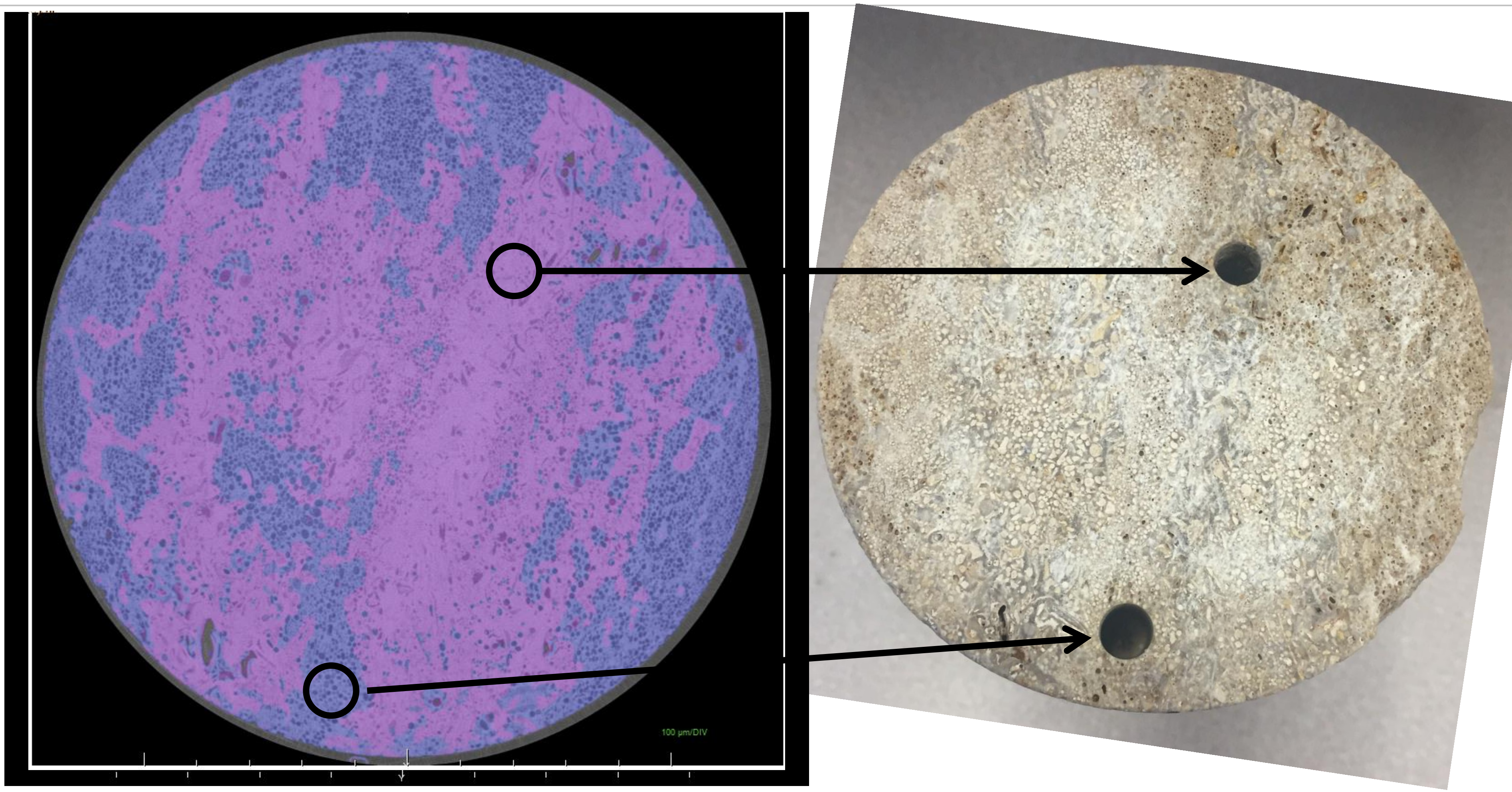
Results
Macroscopic Scan - Interpretation



Results

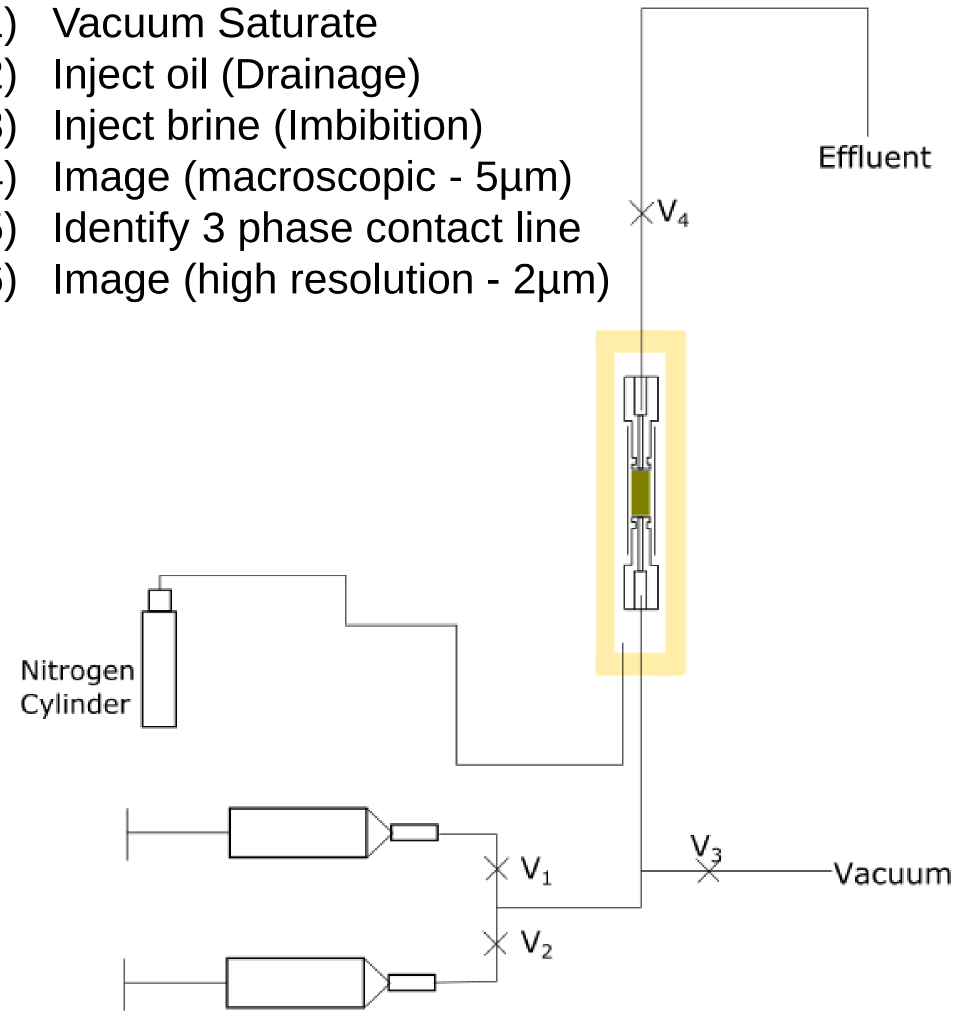
Macroscopic Scan - Classification

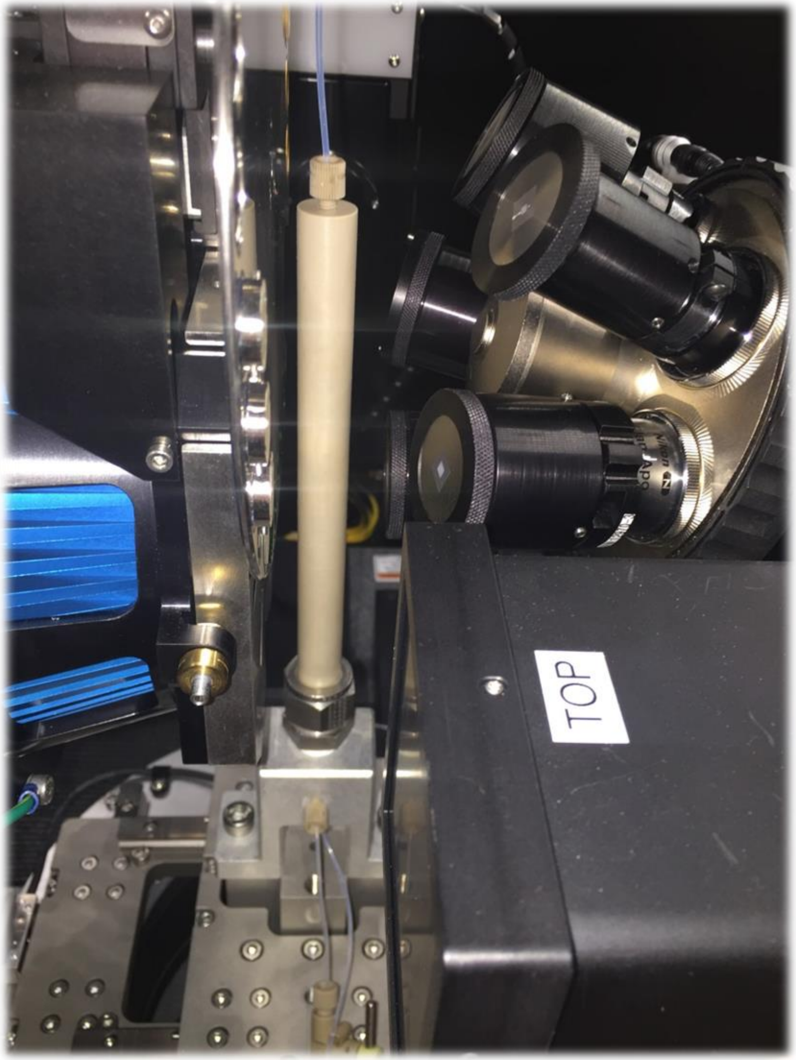
Multi-scale Techniques – Mechanical Sampling



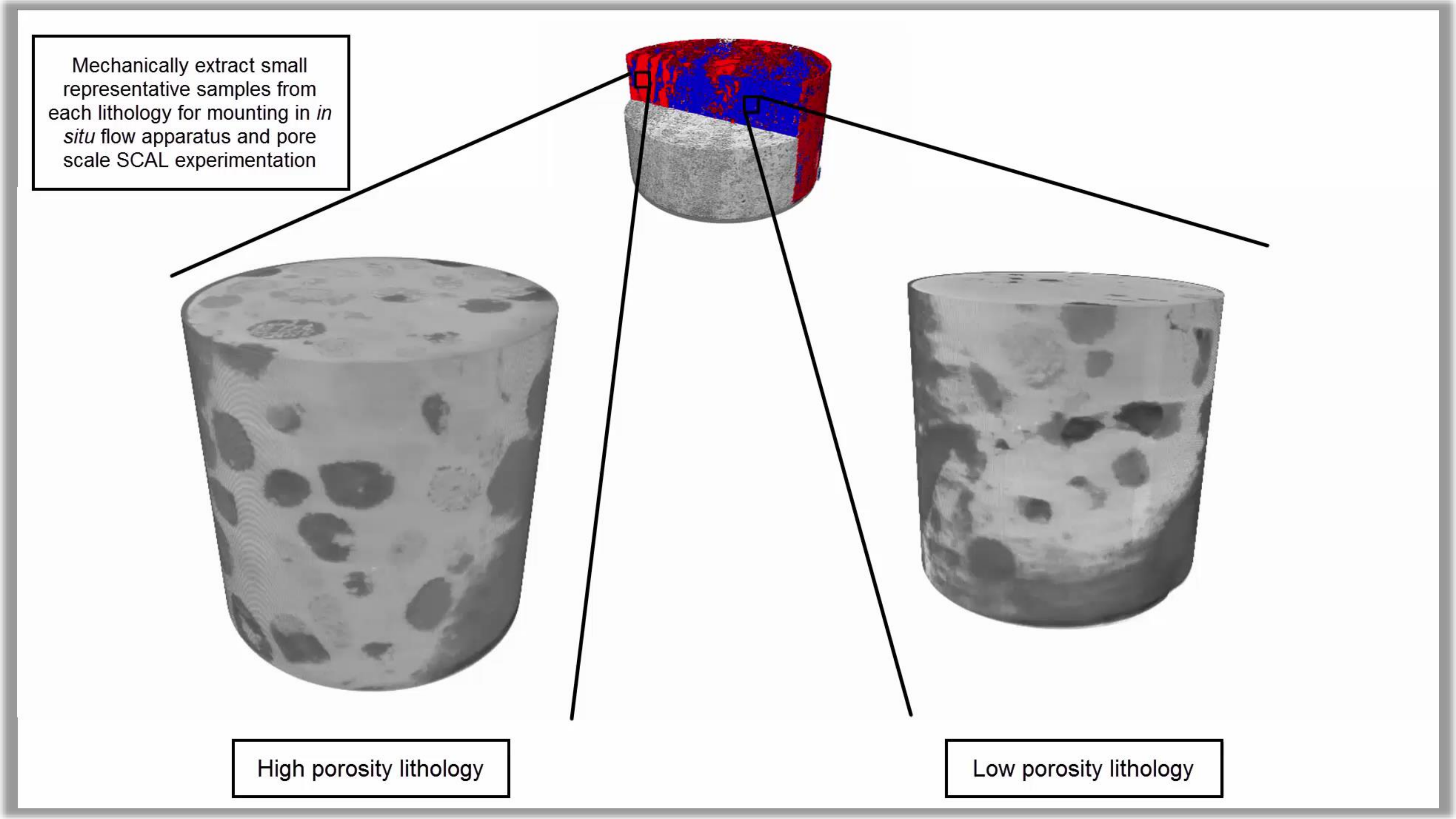
In Situ Experimentation
Custom Rigs & the Integration Kit

1) Vacuum Saturate
2) Inject oil (Drainage)
3) Inject brine (Imbibition)
4) Image (macroscopic - 5µm)
5) Identify 3 phase contact line
6) Image (high resolution - 2µm)



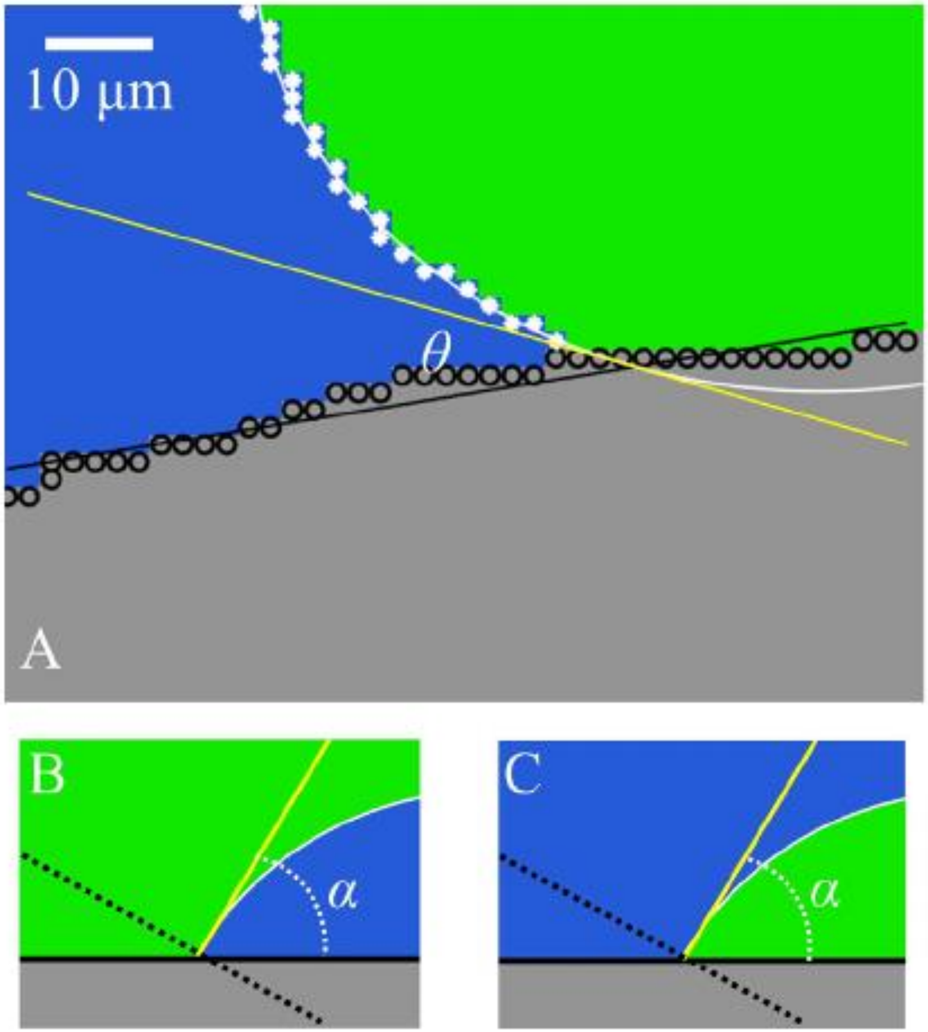


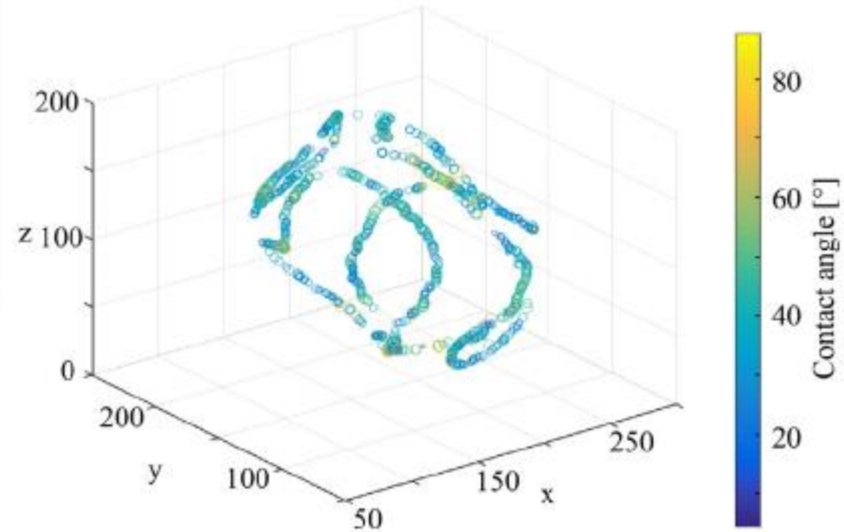
Results:
Pore-scale Wettability of Multiple Lithologies



Causes & Correlative Microscopy

Towards automation





Automatic method for estimation of *in situ* effective contact angle from X-ray micro tomography images of two-phase flow in porous media

Alessio Scanziani [a,b,*], Kamaljit Singh [b], Martin J. Blunt [a,b], Alberto Guadagnini [a,c]

[a] Politecnico di Milano, Dipartimento di Ingegneria Civile e Ambientale, Piazza Leonardo da Vinci 32, 20133 Milan, Italy
[b] Imperial College London, Department of Earth Science and Engineering, London SW7 2AZ, UK
[c] University of Arizona, Department of Hydrology and Atmospheric Science, Tucson, AZ 85721, USA

Automated contact angle estimation for three-dimensional X-ray microtomography data

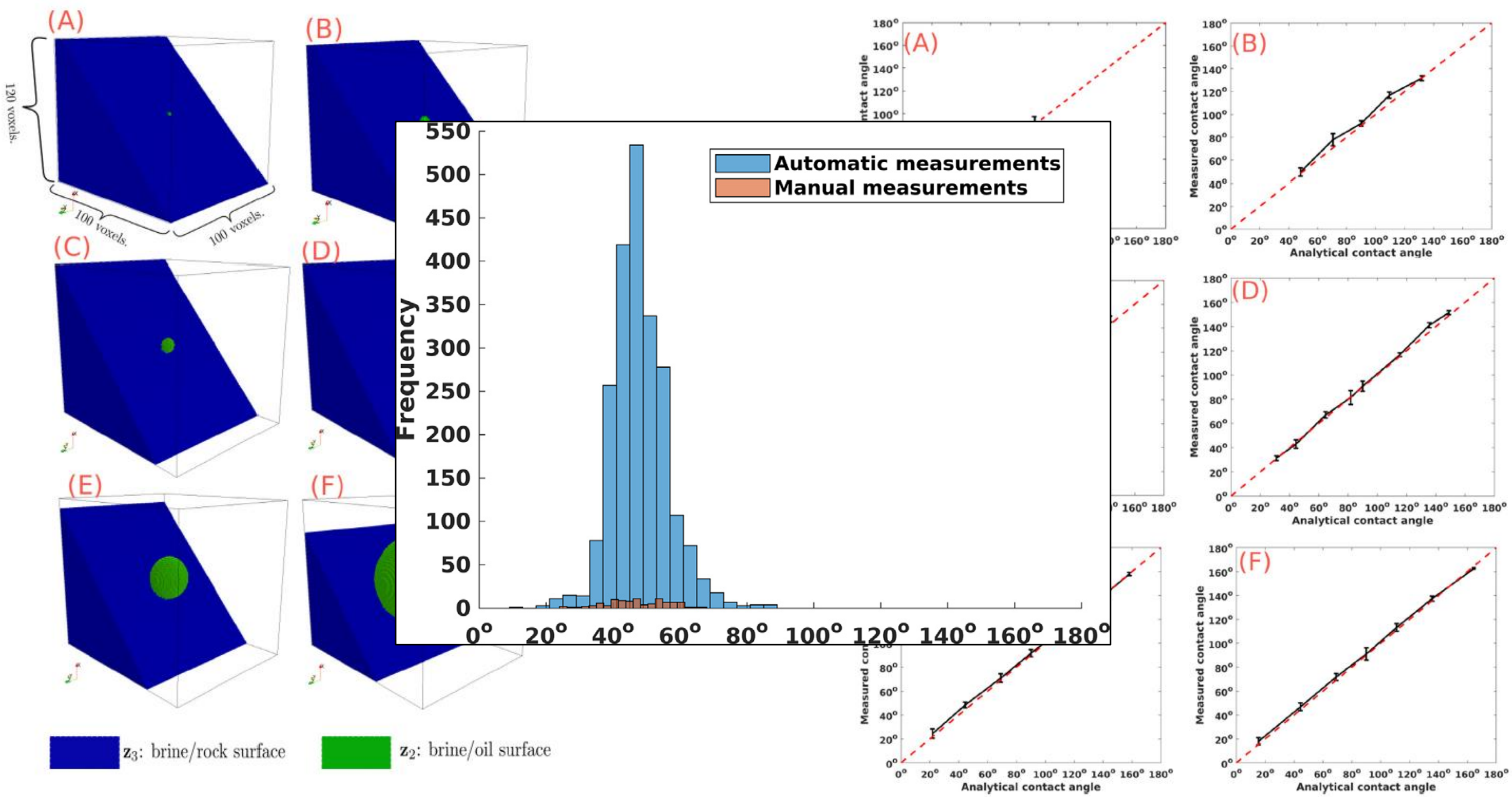
Katherine Klise [a], Dylan Moriarty [a], Hongkyu Yoon [a], Zuleima Karpyn [b]

Towards Automation Propagation

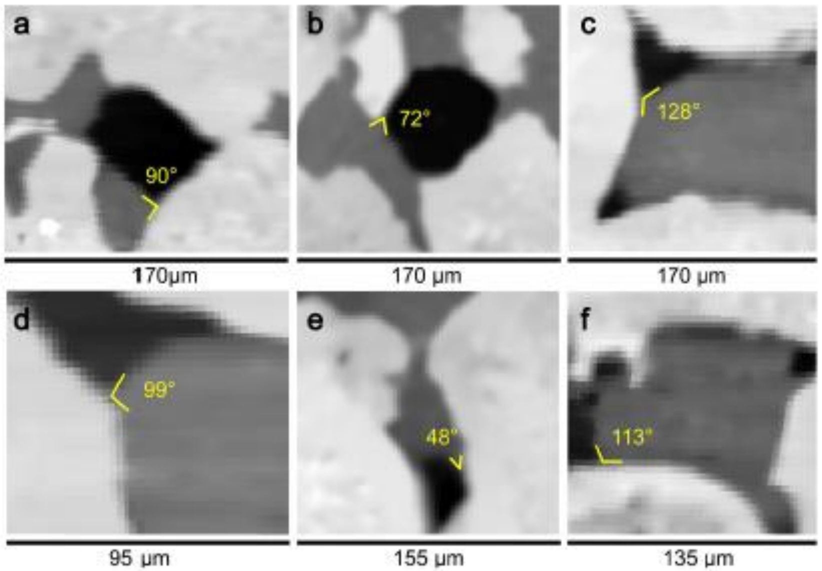
Automatic measurement of contact angle in pore-space images

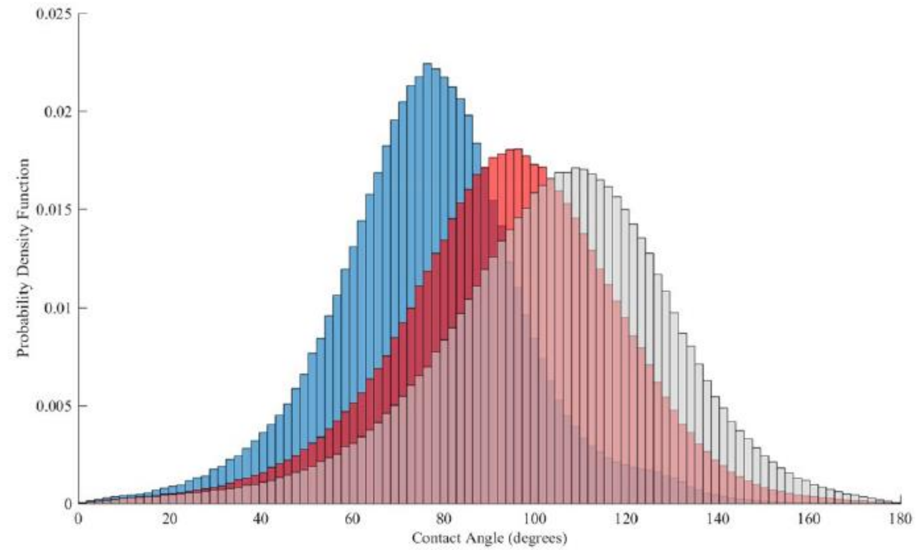
Ahmed AlRatrout*, Ali Q Raeini, Branko Bijeljic, Martin J Blunt

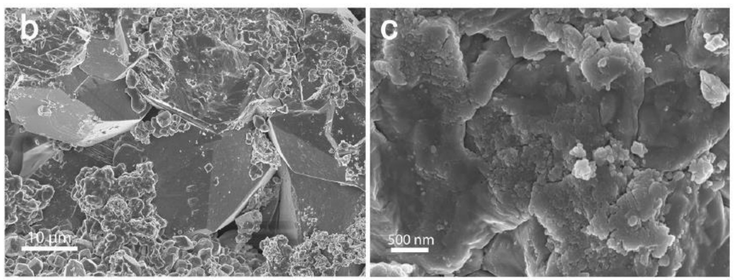
Department of Earth Science and Engineering, Imperial College London, South Kensington Campus, London SW7 2AZ, UK

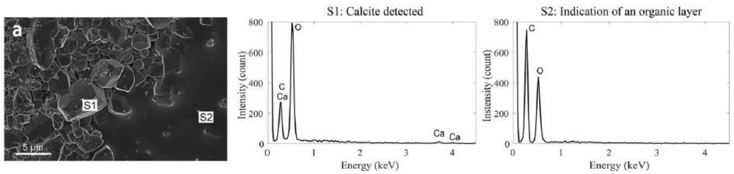


Towards Automation
Real Systems









SCIENTIFIC REPORTS

OPEN

In situ characterization of mixed-wettability in a reservoir rock at subsurface conditions

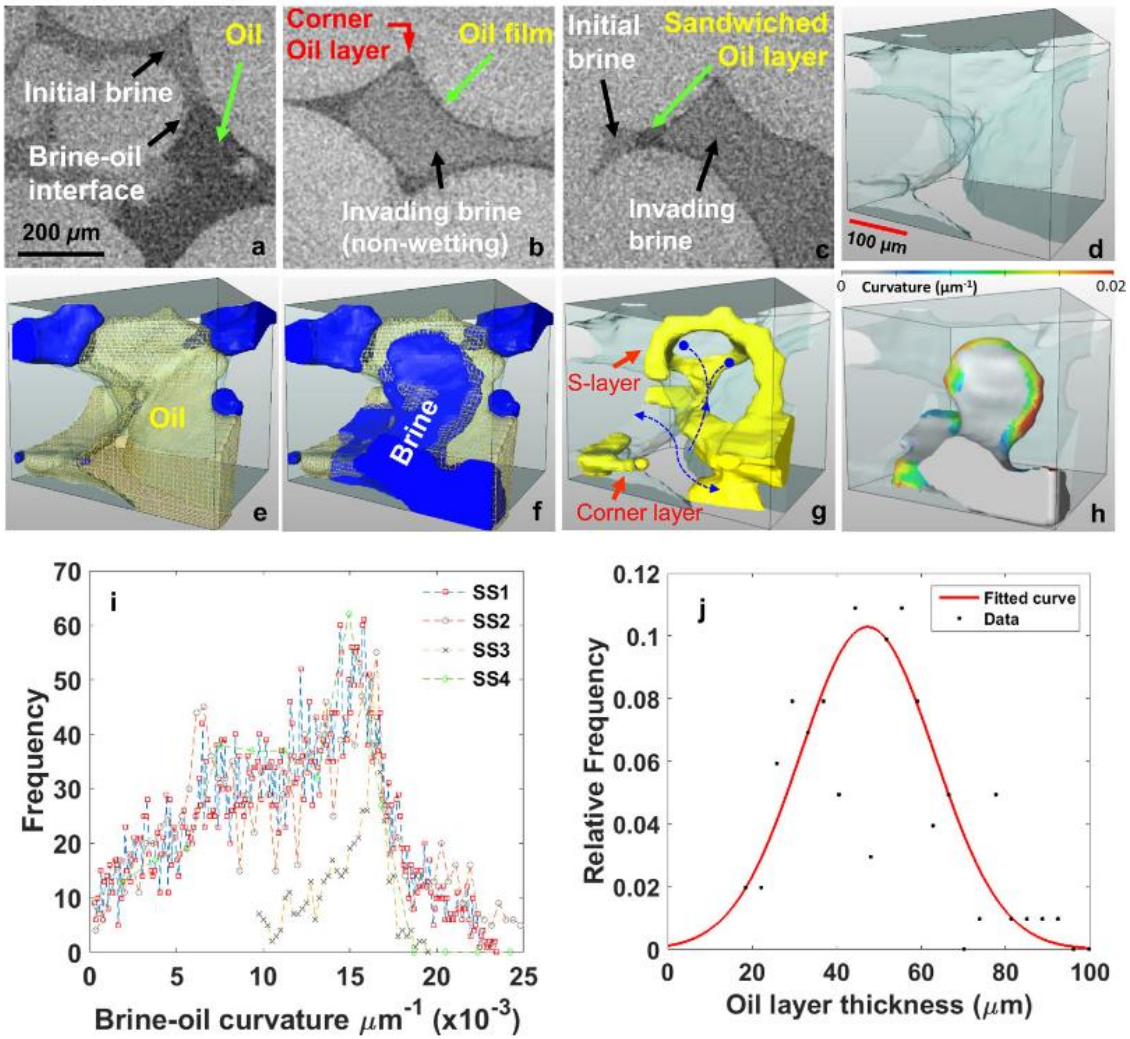
ed: 13 June 2017
ed: 17 August 2017

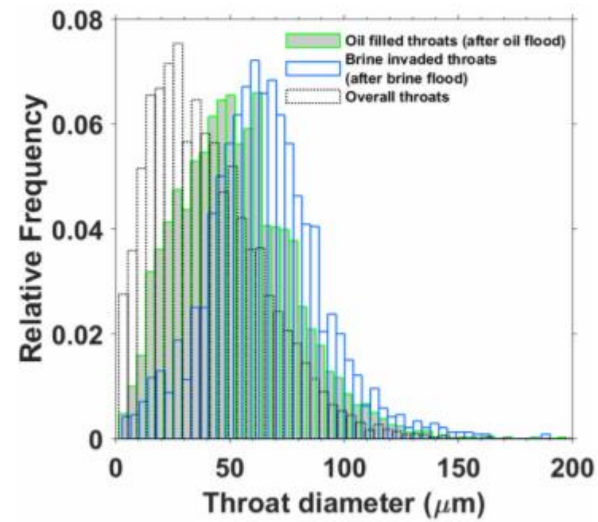
Amer M. Alhammadi, Ahmed AlRatrout, Kamaljit Singh, Branko Bijeljic & Martin J. Blunt

Applications
Oil layer measurement

Imaging of oil layers, curvature and contact angle in a mixed-wet and a water-wet carbonate rock

Kamaljit Singh[1], Branko Bijeljic[1], and Martin J. Blunt[1]

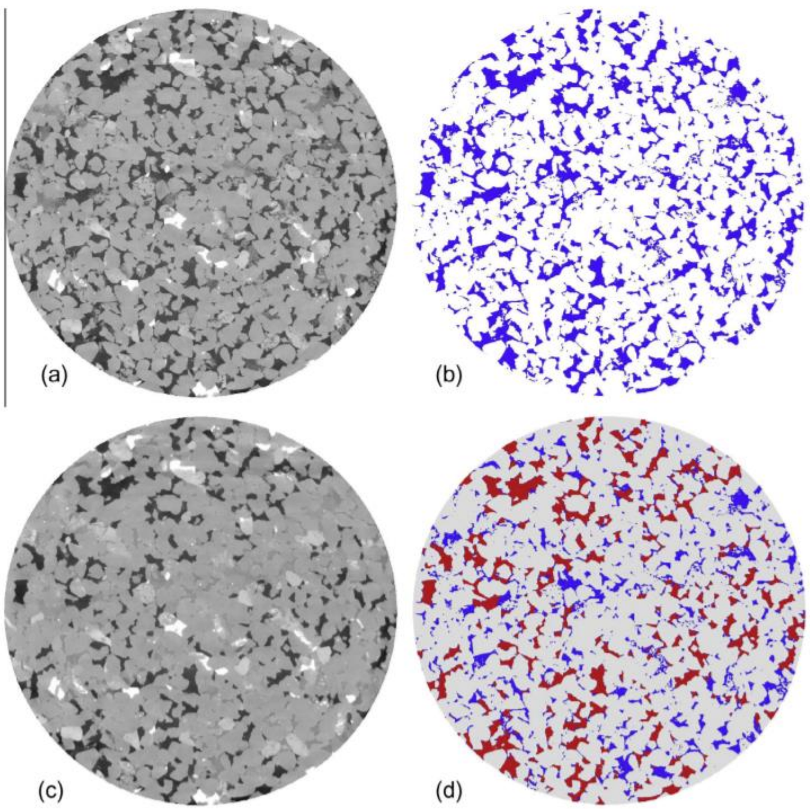


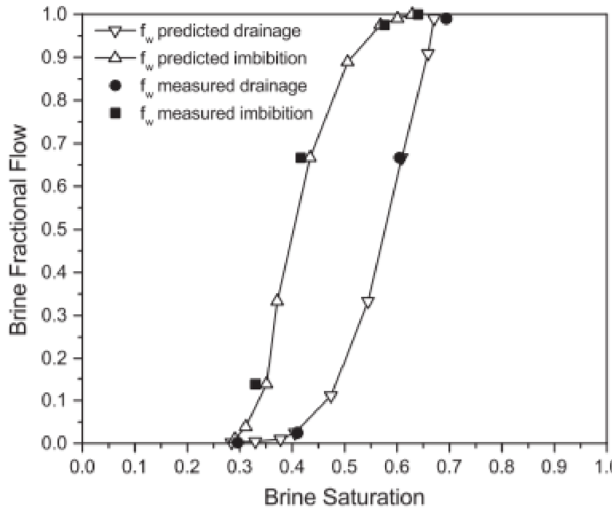


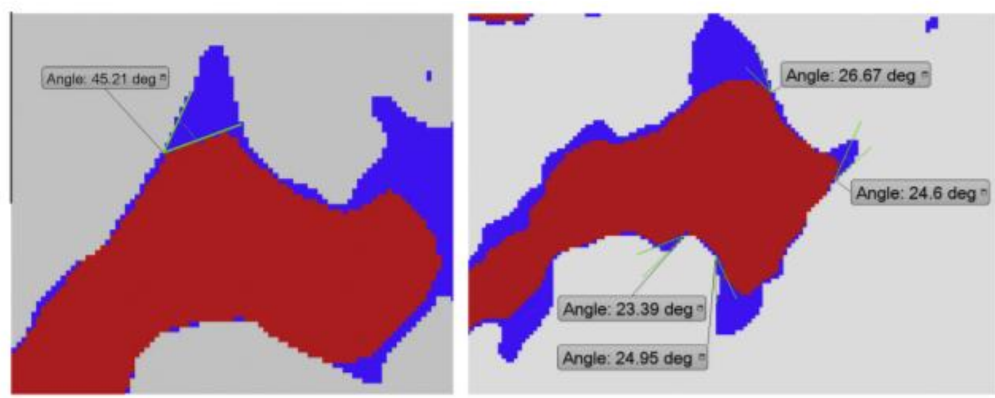
Applications
During steady state flow

Direct pore-to-core up-scaling of displacement processes: Dynamic pore network modeling and experimentation

Arash Aghaei, Mohammad Piri *



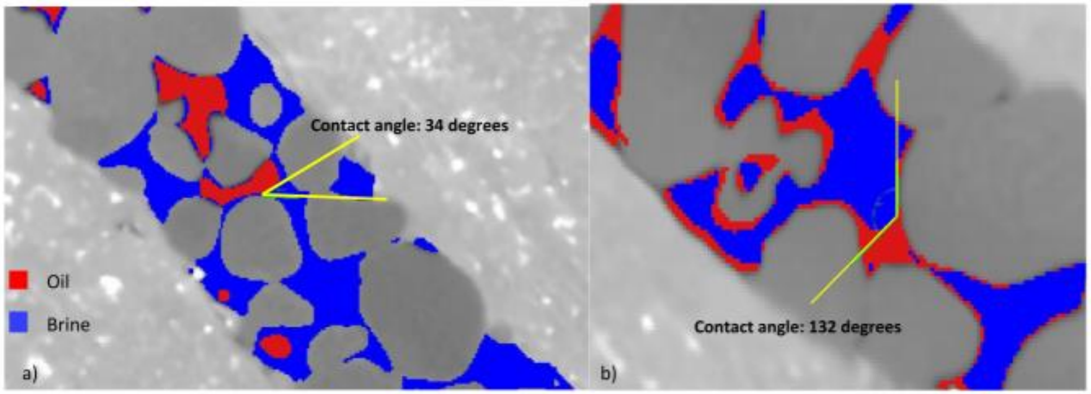


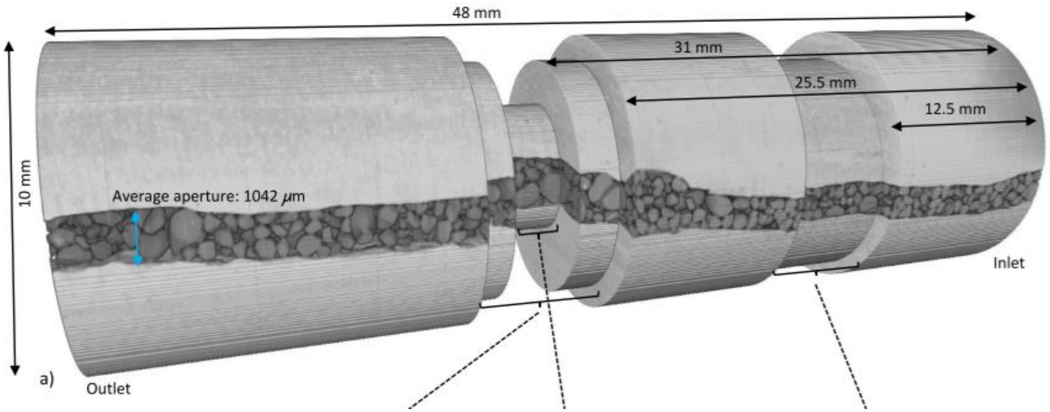


Applications
Proppant embedment

The effect of deformation on two-phase flow through proppant-packed fractured shale samples: A micro-scale experimental investigation

Maziar Arshadi[a,*], Arsalan Zolfaghari[a], Mohammad Piri[a], Ghaithan A. Al-Muntasheri[b], Mohammed Sayed[c]

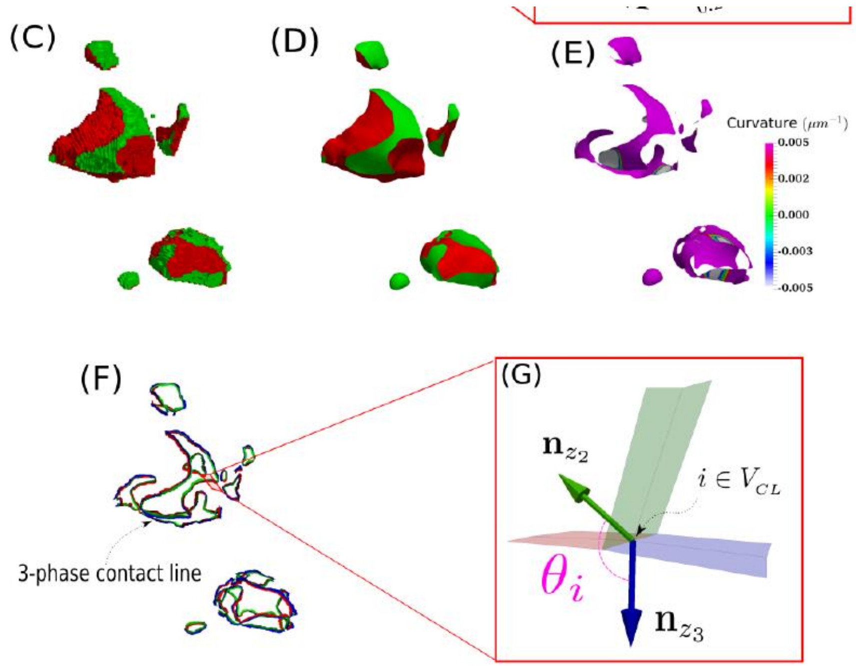


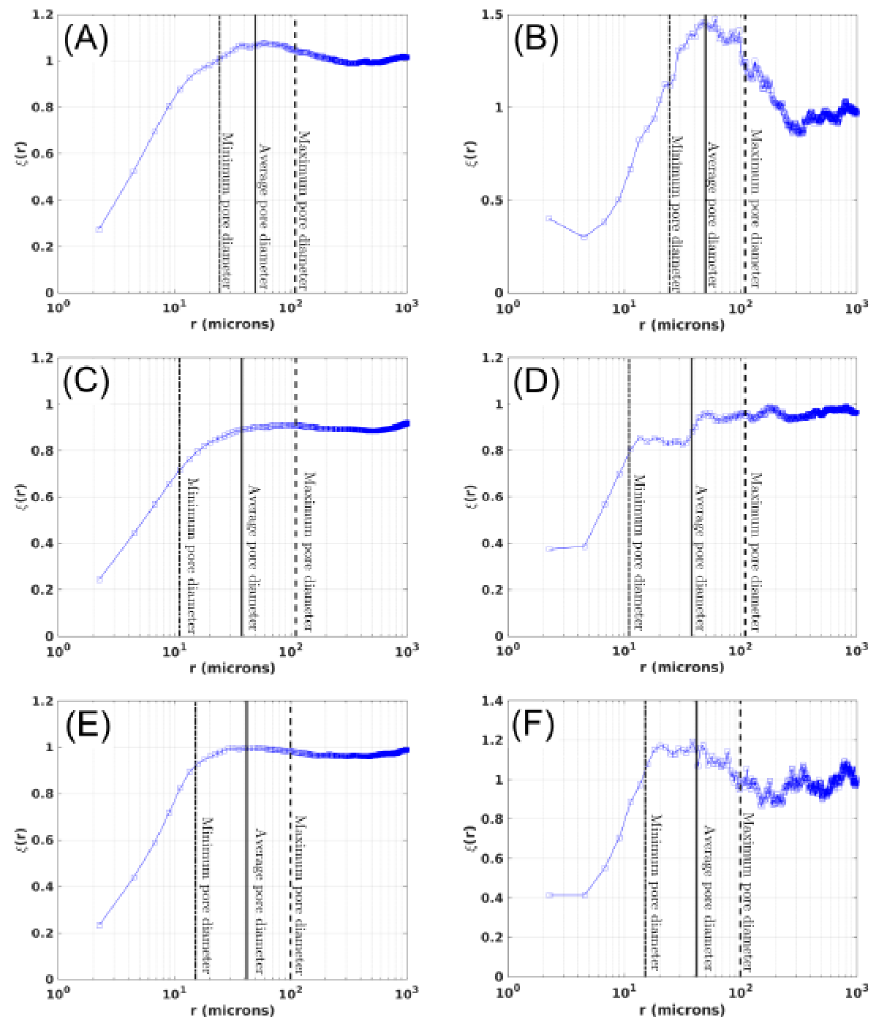


Applications
Contact angle and curvature

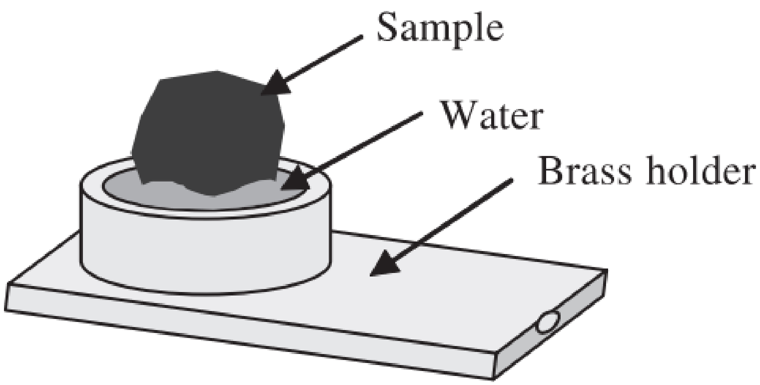
Spatial correlation of contact angle and curvature in pore-space images

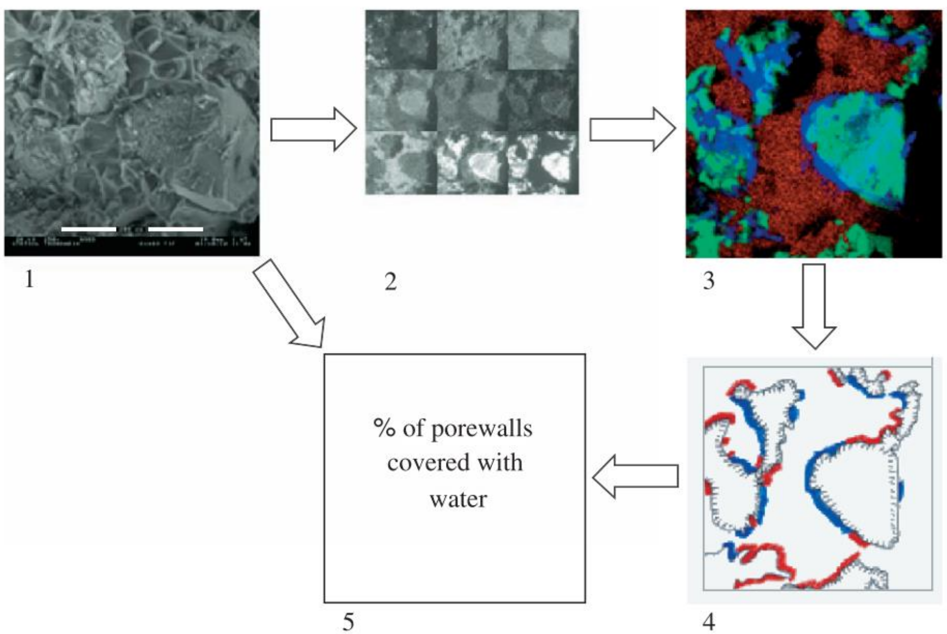
Ahmed AlRatrout, Martin J. Blunt, and Branko Bijeljic

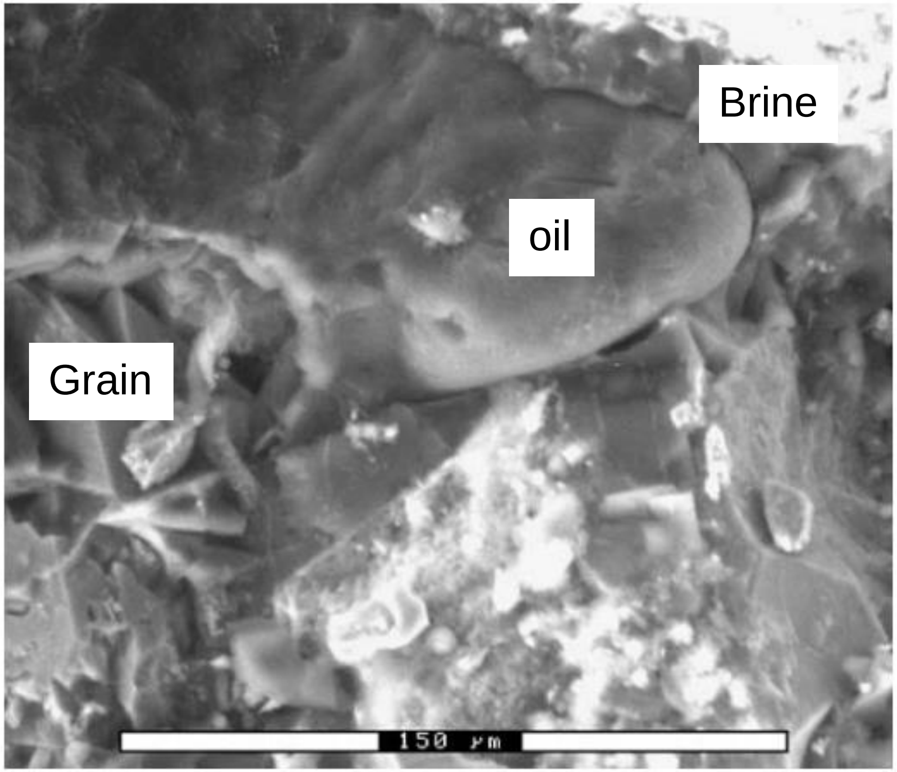




cryo-SEM - origins

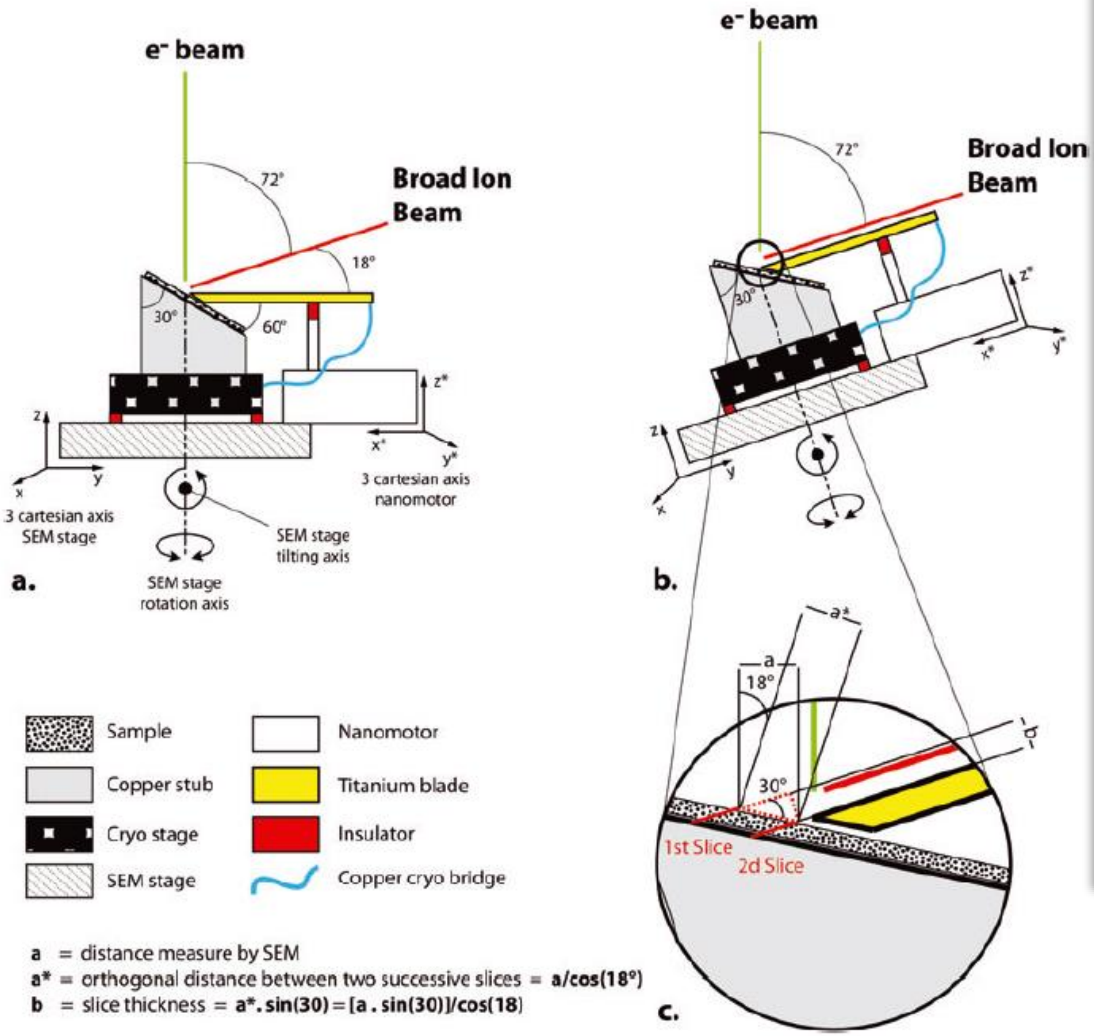






Kowalewski et al. 2003, Journal of Petroleum Science and Engineering, Volume 39, Page 377, DOI: 10.1016/S0920-4105(03)00076-7

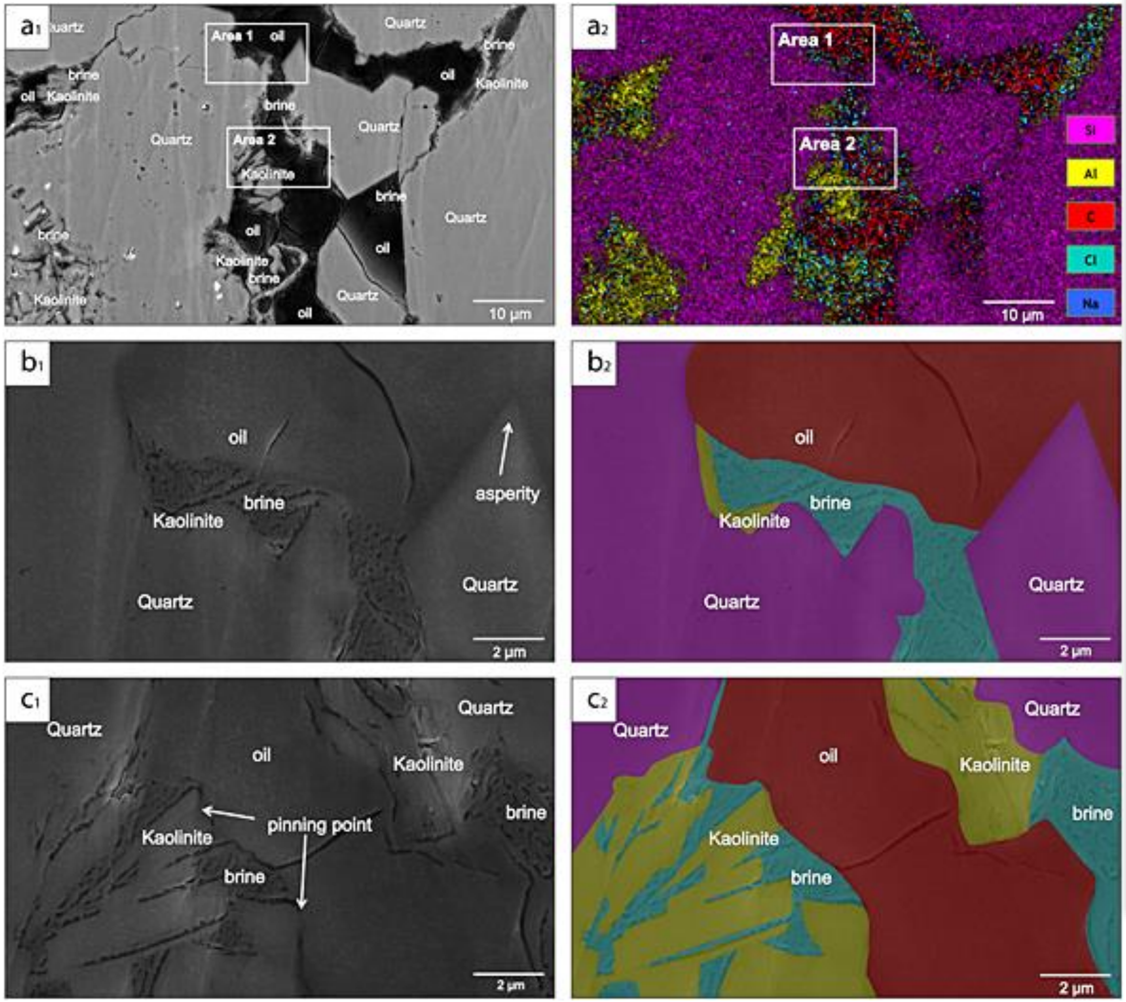
Imaging fluid occupancies using cryo-SEM



- ZEISS SUPRA SEM + custom Cryo BIB system
- Noble gas (argon) Broad Ion Beam used to mill sample
- Serial sectioning enabled by coupled sample stage, milling beam and imaging system
- Titanium BIB mask progressively withdrawn at sequential imaging steps to give high Z thickness accuracy
- Can be coupled with other EM techniques (e.g. EDX mapping) to give quantitative 3D chemical / mineral distributions

Desbois et al. 2013, Journal of Microscopy,
Volume 249, Issue 3, pages 215-235
DOI: 10.1111/jmi.12011

Imaging fluid occupancies using cryo-SEM



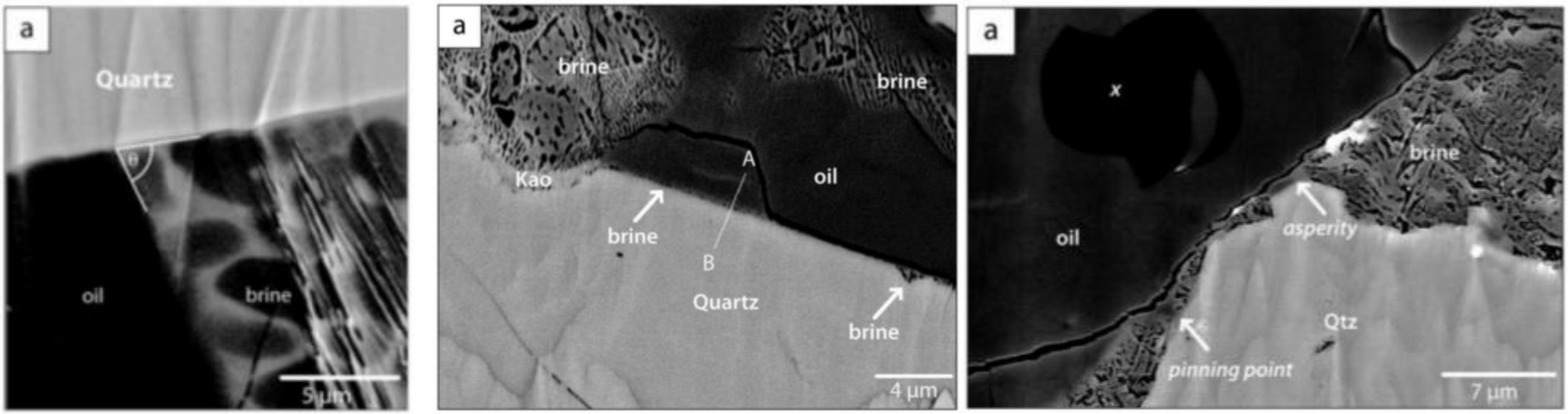
- Pixel Size: 60nm
- Fluids: NaCl Brine, Brent Crude,
- Sample: Obernkirchener Sandstone

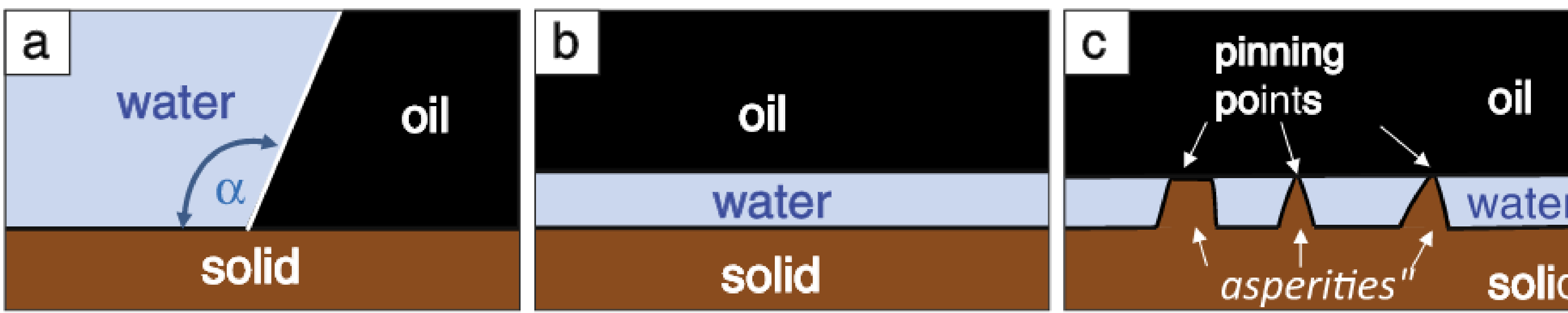
- Quantitative EDX mapping used to map distribution of:
  - Oil
  - Brine
  - Clay
  - Quartz

- Three wetting conditions identified:
  1. Classical contact and contact angle
  2. Oil separated from rock by water film
  3. Local contacts via pinning through asperities – geometrical / chemical heterogeneity

Schmatz et al. 2015, Geophysical Research Letters,
Volume 42, Issue 7, pages 2189-2195
DOI: 10.1002/2015GL063354

Imaging fluid occupancies using cryo-SEM





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Matthew Andrew, PhD